Astronomy & Astrophysics manuscript no. gl581-arXiv
(DOI: will be inserted by hand later)

February 5, 2008

The HARPS search for southern extra-solar planets ⋆

VI. A Neptune-mass planet around the nearby M dwarf Gl 581

X. Bonfils[1,2], T. Forveille[3,1], X. Delfosse[1], S. Udry[2], M. Mayor[2], C. Perrier[1]
F. Bouchy[4], F. Pepe[2], D. Queloz[2], and J.-L. Bertaux[5]

[1] Laboratoire d'Astrophysique, Observatoire de Grenoble, BP 53, F-38041 Grenoble, Cédex 9, France
[2] Observatoire de Genève, 51 ch. des Maillettes, 1290 Sauverny, Switzerland
[3] Canada-France-Hawaii Telescope Corporation, 65-1238 Mamalahoa Highway, Kamuela, HI96743, Hawaii, USA
[4] Laboratoire d'Astrophysique de Marseille, Traverse du Siphon, 13013 Marseille, France
[5] Service d'Aéronomie du CNRS, BP 3, 91371 Verrires-le-Buisson, France

Received / Accepted

Abstract. We report the discovery of a Neptune-mass planet around Gl 581 (M3V, M = 0.31 $M_\odot$), based on precise Doppler measurements with the HARPS spectrograph at La Silla Observatory. The radial velocities reveal a circular orbit of period P = 5.366 days and semi-amplitude K_1 = 13.2 m s^{-1}. The resulting minimum mass of the planet ($m_2 \sin i$) is only 0.052 M_{Jup} = 0.97 M_{Nep} = 16.6 M_{Earth} making Gl 581b one of the lightest extra-solar planet known to date. The Gl 581 planetary system is only the third centered on an M dwarf, joining the Gl 876 three-planet system and the lone planet around Gl 436. Its discovery reinforces the emerging tendency of such planets to be of low mass, and found at short orbital periods. The statistical properties of the planets orbiting M dwarfs do not seem to match a simple mass scaling of their counterparts around solar-type stars.

Key words. Stars: individual: Gl 581 – Stars: planetary systems – Stars: late-type – Techniques: radial-velocity

1. Introduction

Over 150 planets have been found orbiting main sequence stars other than the Sun, in about 140 planetary systems of which 18 have multiple planets (http://vo.obspm.fr/exoplanetes/encyclo/). These extra-solar planets are a very diverse class: their mass ranges between half the mass of Neptune and 15 times the mass of Jupiter, some have large eccentricities when others have nearly circular orbits, their periods range from slightly over a day (Konacki et al., 2003, OGLE-TR-56) to over a decade (Marcy et al., 2002, 55 Cnc). The multiple systems range from strongly resonant to fully hierarchical (Rivera et al., 2005; Marcy et al., 2002). This diversity demonstrates that our own solar system represents but one possible outcome of the planetary formation and evolution processes, and apparently not even a very common one.

The statistical properties of these exoplanets provide crucial clues to their formation mechanism. As perhaps the most dramatic example, the seminal detection of the 51 Peg planet in a 4-days orbit (Mayor & Queloz, 1995) immediately forced theoreticians to recognize the critical importance of orbital migration (Lin et al., 1996; Ward, 1997). The correlation between the occurence of Jupiter-mass planet and the high metallicity of the host stars (Gonzalez, 1997; Santos et al., 2001, 2004) is another exemple. It is thought to reflect the controlling role of the condensate mass in the protoplanetary disk, but it has taken longer to converge towards that consensus.

To date, all but 2 of these 140 planetary systems orbit solar-type stars. In part, this no doubts reflects a bias of most planet-search programmes towards the relatively bright F to K main sequence stars, and away from their fainter M-type counterparts (M < 0.6 $M_\odot$). Nonetheless, several teams (Wright et al., 2004; Endl et al., 2003; Delfosse et al., 1998a) collectively monitor over 200 M dwarfs with sufficient precision to detect a Jupiter-mass planet out to at least 2 AU. These efforts have up to now identified the 3-planet system around Gl 876 (Delfosse et al., 1998a; Marcy et al., 1998, 2001; Rivera et al., 2005), and the single-planet Gl 436 system (Butler et al., 2004). Of these 4 planets, 2 are in the Neptune-mass class, leaving only two of the Gl 876 planets with approximately Jupiter-mass. By constrast ≥5% of solar-type stars have Jupiter-mass planets (Marcy et al., 2000), and the comparative deficit for the M dwarfs is therefore statistically robust (Butler et al., 2004; Naef et al. , 2005).

An open question, though, is whether M dwarfs genuinely have fewer planets, or whether their planets are just

⋆ Based on observations made with the HARPS instrument on the ESO 3.6-m telescope at La Silla Observatory under programme ID 072.C-0488

as abundant, but not quite as massive. Addressing this question needs higher precision, or more measurements, than the radial-velocity surveys have achieved to date. To help answering this question, we are using the HARPS spectrograph for a high-precision survey of more than 100 nearby M dwarfs. We present here its first detection, a Neptune-mass planet around Gl 581.

2. Properties of Gl 581

Gl 581 (HIP 74995, LHS 394) is an M3 dwarf (Hawley et al., 1997) with a distance to the Sun of 6.3 pc (π = 159.52±2.27, ESA (1997)). Its photometry (V=10.55±0.01, B−V=1.60 (Mermilliod et al., 1997); K=5.85±0.03 (Leggett, 1992)) and the parallax together result in absolute magnitudes of M_V=11.56±0.03 and M_K=6.86±0.04. From its absolute V magnitude and the 2.08 V-band bolometric correction of Delfosse et al. (1998), the luminosity of Gl 581 is 0.013 $L_\odot$. The Delfosse et al. (2000) K-band mass-luminosity relation, which has much lower intrinsic dispersion than the equivalent V-band relation, gives a 0.31±0.02 $M_\odot$mass, and the Chabrier & Baraffe (2000) theoretical Mass-Radius relation then a radius of 0.29 $R_\odot$. Interestingly, Bonfils et al. (2005) find Gl 581 slightly metal-poor ([Fe/H]=−0.25), in contrast to most planet-host stars having supersolar metallicities.

Gl 581 has been classified as a variable star (HO Lib). However, the data which have led to this classification (Weis, 1994) have a short-term variability of ∼ 0.006 mag. The variability quoted by the author is marginally above the errors bars and, if real, has most likely a long-term nature (several years).

The age of Gl 581 can be estimated from its kinematic characteristics, its magnetic activity, and its metallicity, all of which point towards a moderate to older age. Leggett (1992) find that its UVW galactic velocities are intermediate between those typical of the young and old galactic disk, and Delfosse et al. (1998) find very low X-ray emission ($L_x/L_{bol} < 5.10^{-6}$) and a 2.1 km s^{-1} upper limit on the projected rotation velocity, v sini. The HARPS spectra show weak Ca_{II} H and K emission, in the lower quartile of stars with similar spectral types (Fig. 1). As mentioned above, Gl 581 also has a subsolar metallicity. Altogether, these properties suggest that it is at least 2 Gyr old, and they ensure that the radial velocity "jitter" from magnetic activity must be minimal.

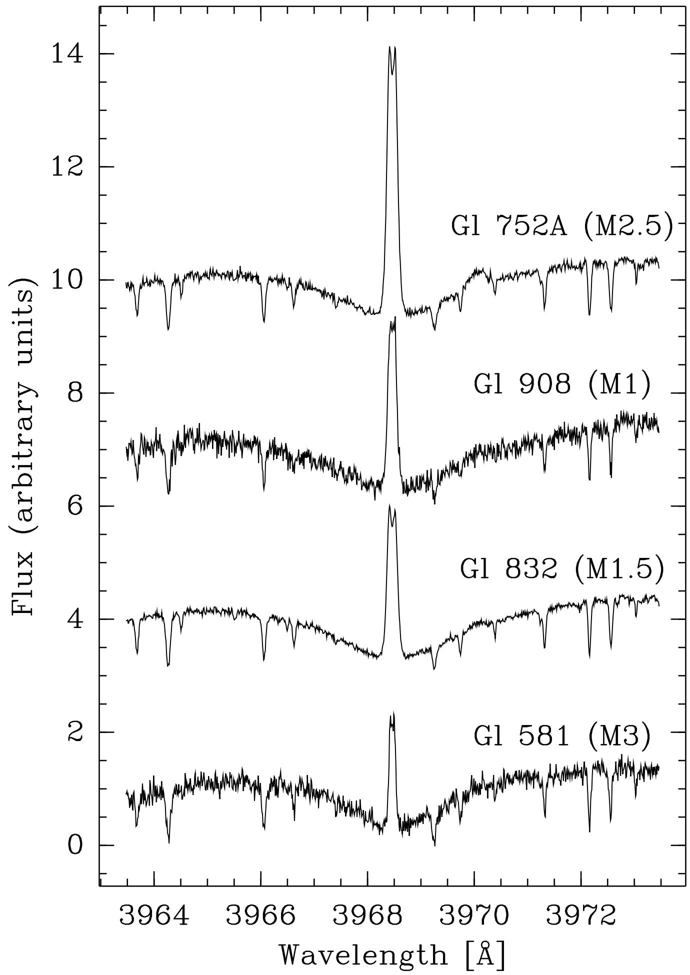

Fig. 1. HARPS spectra of the Ca II H (λ = 3968.47 Å) line region for Gl 581 and three comparison stars with similar spectral type and apparent magnitude. The stars are displayed in order of ascending chromospheric activity, and from top to bottom are Gl 752A, Gl 908, Gl 832 and Gl 581. The chromospheric emission peaks look prominent against the weak blue continuum of these M dwarfs, but they actually denote very weak chromospheric emission relative to the bolometric luminosity. Amongst those 4 stars, Gl 581 has the weakest chromospheric activity.

3. Doppler measurements and orbital analysis

HARPS (High Accuracy Radial velocity Planet Searcher) is the new ESO high-resolution (R = 115 000) fiber-fed echelle spectrograph, optimised for planet search programmes and asteroseismology. It has proved to be the most precise spectro-velocimeter to date, reaching an instrumental RV accuracy better than 1 m s^{-1} (Mayor et al., 2003; Santos et al., 2004a; Pepe et al., 2004; Lovis et al., 2005), and even better on the short-term scales of interest for asteroseismology. For ultimate radial velocity precision HARPS uses simultaneous exposures of a thorium lamp through a calibration fiber. When observing M dwarfs however, we rely instead on its very high instrumental stability (nightly instrumental drifts < 1 m s^{-1}). The M dwarfs are typically too faint for us to reach the stability limit of HARPS within realistic integration times, and dispensing with the simultaneous thorium light produces much cleaner stellar spectra, suitable for quantitative spectroscopic analyses.

For the V = 10.5 Gl 581 we use 15 mn exposures, and the median S/N ratio of our 20 spectra is 40 per pixel at 550 nm. The radial velocities (Table 2, only available electronically) were obtained with the standard HARPS reduction pipeline, based on the cross-correlation with a stellar template and the precise nightly wavelength calibration with ThAr spectra (Baranne et al., 1996). They have a median internal error of only 1.3 m/s, which includes both the nightly zero-point calibration uncertainty (∼ 0.8 m s^{-1}) and the photon noise, computed from the full Doppler information content of the spectra (Bouchy et al., 2001).

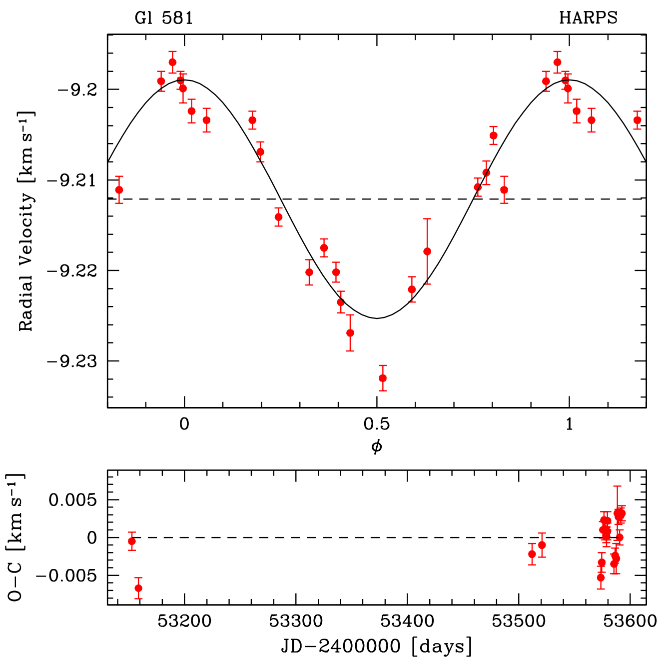

Fig. 2. *Upper panel:* Phased radial velocities for Gl 581. *Lower panel:* Residuals around the fitted solution versus time.

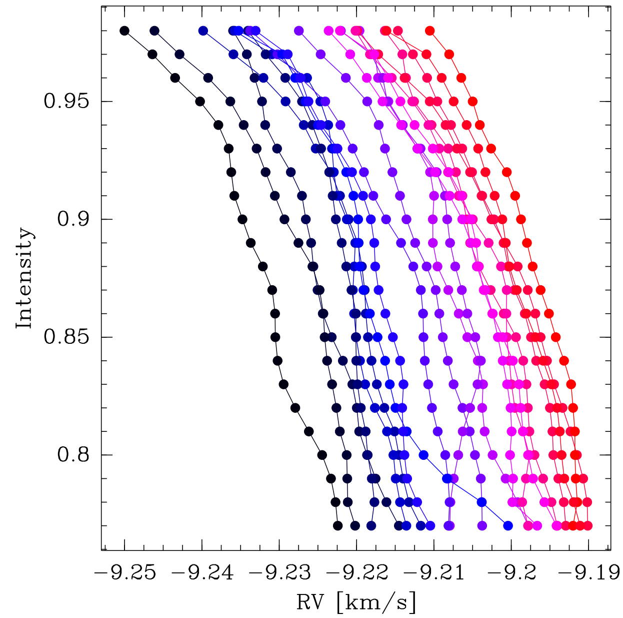

Fig. 3. Bissectors of the HARPS correlation profiles for Gl 581. The shape of the bissector curve does not change together with its position. It validates the planetary interpretation as the cause of the radial-velocity variation.

The computed velocities exhibit an rms dispersion of 10 m s^{-1}, much above their internal errors and also considerably more than we observe for stars with higher chromospheric activity. Of the three comparison stars with stronger chromospheric emission in Fig. 1, Gl 752 and Gl 832 have enough HARPS radial velocities to measure rms dispersions of 1.2 m/s (from 10 measurements) and 1.8 m/s (from 19 measurements). Rivera et al. (2005) report an rms dispersion of 3.42 m/s for the the third, Gl 908, dominated by their measurement noise.

As demonstrated by Fig.2, a circular orbit of period P = 5.366 d and semi-amplitude K = 13.2 m s^{-1} is an excellent fit to these velocities, as expected from rapid tidal circularisation at this short period. Attempts at adjusting elliptical orbits resulted in non-significant eccentricities. We therefore adopt a circular orbit. Its parameters are listed in Table 1 and lead to a minimum mass ($M\ sin\ i$) for the planet of only 0.052 M_{Jup} = 0.97 M_{Nep} = 16.6 M_{Earth}. The weighted rms of the residuals around the fit is 2.5 m s^{-1}, and twice the internal errors of the measurements. More data points are needed to establish whether this extra dispersion is intrinsic to the star, or whether it could be explained by the presence of a third body in the system. Further credit is given to the latter hypothesis by the very-low variability level in the shape of the bisector (Fig 3). An overall translation dominates the evolution of the spectral profile, leaving no doubt on the keplerian origin of the radial-velocity variations. We also have available 11 ELODIE spectra, which extend the measurement baseline to 9 years, albeit with a 5 years gap between mid-2000 and mid-2005. Their 17 m/s median error bars are too large to reveal the K=13 m s^{-1} planetary signal. They exhibit an rms dispersion of 23 m s^{-1} and lack any obvious long term trend, demonstrating that the

Table 1. Orbital and physical parameters.

Parameter		**Gl 581 b**
P	[days]	5.366 ± 0.001
T	[JD-2400000]	51004.30 ± 0.06
e		0. (fixed)
V	[km s^{-1}]	-9.212 ± 0.001
ω	[deg]	0. (fixed)
K	[m s^{-1}]	13.2 ± 0.4
$a_1 \sin i$	[10^{-3} AU]	0.652 10^{-2}
$f(m)$	[$10^{-9} M_\odot$]	0.1354 10^{-2}
$m_2 \sin i$	[$M_{\rm Earth}$]	16.6
a	[AU]	0.041
$N_{\rm meas}$		20
$S\,pan$	[days]	440
σ (O-C)	[m s^{-1}]	2.5

Gl 581 system contains no Jupiter-mass planet with any period shorter than ≈10 years.

4. Discussion

The semi-major axis of the planetary orbit is only 0.042 AU or 9 solar radii, similar to most close-in planets around solar-type stars. In the natural length unit of its central star however, this amounts to 31 radii of Gl 581. The geometric transit probability is thus only 3%, and significantly less than the ≈10% typical of close-in planets around solar-type stars. If transits do occur on the other hand, the planet will cover a larger fraction of its smaller star. For a constant planetary radius, transits would thus be correspondingly deeper and more easily detected. At this radius and given the 0.013 $L_\odot$ luminosity of the star, the expected temperature of the planetary surface is ≈420 K, with large uncertainties from the unknown albedo and energy trans-

port. Even with conservative error bars though, this temperature is compatible with either a rocky planet or a gas giant, and evaporation will be negligibly small in either configuration.

The detection of Gl 581b brings the inventory of M-dwarf which harbor planetary systems to 3, and the number of their planets to 5. While admittedly still very small, these samples allow us an initial peek at their properties as a population, compared to the much more numerous planets known around solar-type stars. One immediate observation is that none of the three stars is metal-rich, with Gl 876, Gl 436 and Gl 581 having metallicities of respectively [Fe/H]=−0.03, +0.02 and −0.25 dex (Bonfils et al., 2005). This contrasts with the median metallicity for solar-type stars surrounded by planets, [Fe/H]=+0.2 (Santos et al., 2005), though the significance of the difference is obviously still modest.

As discussed in the introduction, various groups monitor over 200 M dwarfs with 3-15 m s^{-1} precision, sufficient to easily detect the >40 m s^{-1} reflex motion of a 0.3$M_{\odot}$ star orbited by a Jupiter-mass planet out to 2 AU. That these efforts have to date found only 5 planets, of which only Gl 876b and c have approximately jovian masses, demonstrates that there are much fewer $\approx M_{Jup}$ planets around M dwarfs than the ≈5% (Marcy et al., 2000; Naef et al. , 2005) found around solar-type stars. The 5 planets include no hot-Jupiter, but with only ∼1% solar-type star orbited by such a planet the significance of that fact is still modest. 3 of the 5 on the other hand are hot-Neptunes (Gl 436b, M sin i=1.2 M_{Nep}; Gl 876d, 0.44 M_{Nep}; Gl 581b, 0.99 M_{Nep}), as many as currently known around all solar-type stars. This matches the theoretical model of Ida & Lin (2005): the mass-distribution of close-in planets has two peaks centered at about the masses of Jupiter and Neptune, with the former preferentially populated around G-dwarfs and the latter around M dwarfs, reflecting how much matter remains available in the disk for accretion during the inward migration of the planet. Other theoreticians however take the view that many hot-Neptunes are actually evaporated hot-Jupiters (Baraffe et al., 2005). Better statistics on M-dwarf planets will help determine which of these mechanisms dominate.

A final striking characteristic of the current M-dwarf planets is that none has a period longer than the 2 months of Gl 876b. By contrast, 66% of the 164 planets known around solar-type stars have orbital periods above 100 days and their distribution is even observed to increase with period (Udry et al., 2003). With 5 planets known around M dwarfs, the probability that the long-period deficit amongst M-dwarf occurs by chance is thus less than $(0.34)^5$=5.10^{-3}. The sensitivity of Doppler searches does degrade for longer periods however, and planets of M dwarfs have often been found close to the sensitivity floor of their respective discovery surveys, making detection biases potentially important. A full account is not currently possible from published information (our own high precision M-dwarf survey is still too recent to be very useful in this respect), but for periods shorter than the observing interval the sensitivity degrades only slowly (∝P−1/3). Some of the M-dwarf Doppler surveys have been observing for long enough (Bonfils et al., 2004; Butler et al., 2004) that detection biases make an unlikely full explanation for the lack of long period planets. That deficit therefore has to be at least in part intrinsic, perhaps reflecting smaller protoplanetary disks around the lower mass M dwarfs.

Acknowledgements. We thank our technical and scientific collaborators of the HARPS Consortium, ESO Head Quarter, and ESO La Silla, who have contributed with passion and competence to the success of the HARPS project. We are also grateful to Damien Ségransan who contributed additional ELODIE observations, and to Jean-Christophe Leyder and collaborators for using some of their own observing time to obtain critical confirmation observations.

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Table 2. Radial-velocity measurements and error bars for Gl 581. All values are relative to the solar system barycenter. Only available electronically

JD-2400000	**RV** [km s^{-1}]	**Uncertainty** [km s^{-1}]
53152.71289	-9.2235	0.0012
53158.66336	-9.2319	0.0014
53511.77355	-9.2202	0.0014
53520.74475	-9.1999	0.0016
53574.52223	-9.2024	0.0013
53575.48075	-9.2069	0.0011
53576.53646	-9.2202	0.0011
53577.59250	-9.2221	0.0014
53578.51061	-9.2108	0.0010
53578.62960	-9.2092	0.0013
53579.46256	-9.1991	0.0011
53579.62115	-9.1970	0.0012
53585.46167	-9.2034	0.0013
53586.46516	-9.2141	0.0010
53587.46481	-9.2269	0.0020
53588.53827	-9.2179	0.0036
53589.46202	-9.2051	0.0010
53590.46379	-9.1990	0.0010
53591.46638	-9.2034	0.0010
53592.46481	-9.2175	0.0010

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